BEAM DUMP SYSTEM (WBS 1.6)

i. System Introduction

This description of the Beam Dump System was updated in October 2002. A few obsolete sections have been revised or corrected consistent with present knowledge and experience. The original sections described the future – the tense of the verbs has not changed in this revision. Add material describes the past and the present.

An internal beam abort system capable of absorbing the full energy heavy ion beam of the RHIC accelerator once per hour has been designed. The system will be comprised of 3 major subsystems, 1) the kicker magnets, 2) the pulsers and pulse forming networks (PFNs) and 3) the dump absorber. The beam abort systems will be located in the outer straight sections downstream of the 10 o'clock IP between Q3 and Q4 (see Fig. 6-1). In this configuration, the lattice parameters favor extraction in the horizontal plane. The kickers, actually composed of five modules, will be located at Q3 downstream of the crossing point. They will deflect the beam horizontally towards the ring center, onto the C-C absorber whose front face will be 23.5 m downstream from the midpoint of the kicker modules, and just upstream of Q4.

The energy stored in the beam will be about 200 kJ at top energy for all species assuming 60 bunches with nominal intensity, i.e. 10^9 in the case of gold beams. This energy is large enough to cause component damage if lost in an uncontrolled manner, but small enough to be disposed of in an internal beam dump system provided that the expected secondary particle spray from the dump absorber can be contained sufficiently well so as not to overheat and, thus, quench the superconducting magnets downstream. The stored beam energy can be disposed of within the constraints of the lattice without damage to the equipment provided that the materials in the dump absorber have been carefully chosen and the beam is dispersed over a sufficiently large area on the face of the dump absorber.

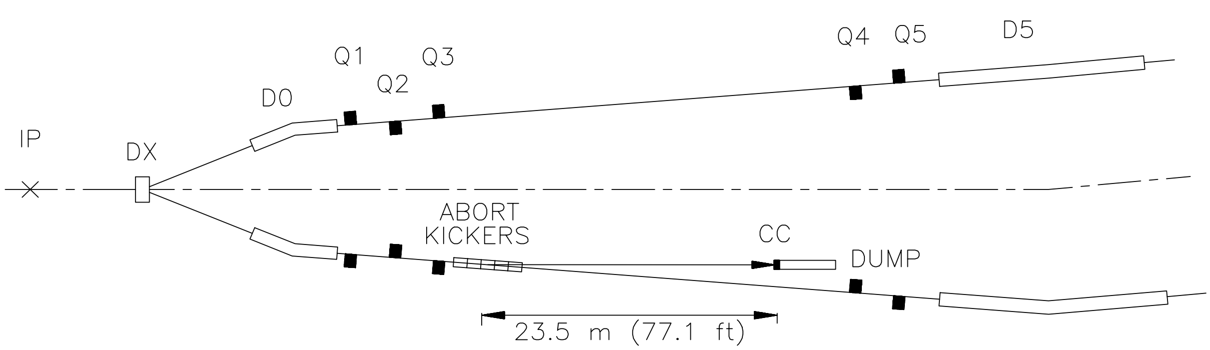

Fig. 6-1. Location of abort kickers and beam dump in the yellow ring at 10 o'clock.

The abort system will be used routinely to safely dump beam when the luminosity has declined to an unacceptable level or whenever deviations from normal operations are detected which may cause the beam to stray beyond a safe region within the vacuum chamber. The system response time will be sufficiently fast to begin safe extraction of the beam in all conceivable cases of accidents or beam instabilities within 4 turns (~52 μsec), and the beam will then be aborted within a single turn (~13 μsec). The 'as built' response time is slightly slower than originally planned. The pulse-forming system delivering the current pulse to the magnets requires approximately a 1–turn delay period to allow the charging supply to be disconnected from the pulse-forming network. The trigger synchronization requires up to another turn. These add to the originally planned delays for sensing fault conditions and transmitting that information to the abort system to begin the abort process. However, a few additional turns of delay do not affect the efficient functioning of the system.

The task will be to eject a small, potentially damaging beam which is traveling inside a larger "dump aperture," i.e. the phase space permitted by physical apertures in the collider. In the event of malfunction, when an incipient excursion toward a physical aperture is detected, the abort system will react quickly enough so that the beam has no chance to escape the dump aperture altogether. At the same time, however, control over the exact beam position or size will be already deteriorating. Therefore, not only the beam, but the entire dump aperture phase space must be transposed onto the dump absorber. This requirement determines the apertures of physical elements within the beam dump channel. The 18 m long beam tube between the five kicker modules and beam dump has the standard warm bore dimensions of 12.7 cm o.d. The layout of the dump components and their locations within the 10 o'clock tunnel structure are shown in Fig. 6-2.

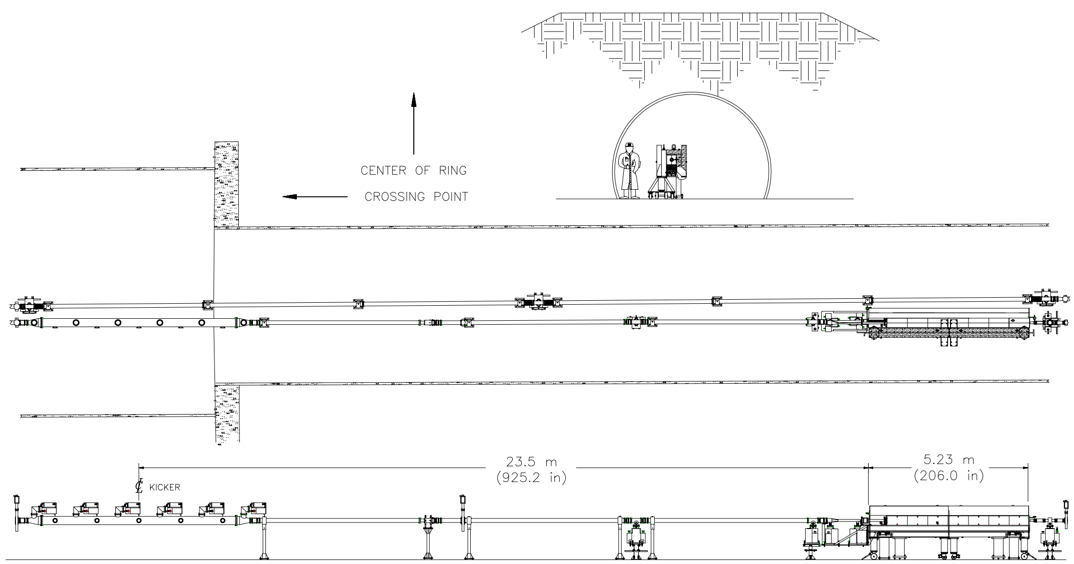

Fig. 6-2. Placement of beam dump components within Collider tunnel. Area shown is yellow ring at 10 o'clock.

In the RHIC rings, physical aperture requirements are determined at injection, with $\beta^*=$ 10 m at all crossing points, to accommodate a 6σ beam halo for gold beams, whose transverse emittance has been enlarged to 15π mm·mrad (from the nominal normalized 10π) by intrabeam scattering. The corresponding (un-normalized) dump aperture is ~7π mm.mrad. In practice, after establishing running conditions at top energy (where physical apertures exceed 10σ, even after intrabeam scattering has enlarged the emittance to 40π mm·mrad), a collimator will be inserted into the beam halo in each ring. A rapid increase in losses on these limiting aperture collimators is expected to be the most likely trigger for the abort system should malfunction occur.

The kicker system must operate over the range of energies from RHIC injection to the maximum energy of RHIC ($B\rho$ = 97.5 to 839.5 T.m). The nominal deflection angle required of the kicker system will be 1.6 mrad at all energies. The total magnetic length of the five kicker magnets is 6.10 m, which then requires a nominal magnetic field strength of 0.22 T in each magnet for the highest RHIC energies to ensure adequate deflection angle. In order to avoid uncontrolled beam loss in case of a single pulser or magnet failure, the kicker module will be built of five individual magnets, each with its own pulser. In the event of a failure to fire of a magnet or pulser, the 80% deflected beam (1.28 mrad) will still clear the limiting aperture of 17.75 mm in the dump and project onto an ellipse having a horizontal extent of ±11.3 mm on the face of the dump absorber. Because of the aspect ratio of the length to diameter dimensions of the structure, it is difficult to visualize the path of the circulating and ejected beams. Figure 6-3 shows this area schematically, with a normal longitudinal scale, but with transverse dimensions increased by a factor of 50. The horizontal beam envelopes of ±11.3 mm width are shown for both the nominal minimum and maximum kicker deflections as they impact the absorber face.

The anticipated failure mode mentioned above where one module fails to fire, which in part motivated the specification for the number of modules to be used, has not occurred in practice. The primary failure mode has been the "prefiring" of one of the five modules with the collider operating with fully loaded rings, at collision energy, and with the Beam Experiment detectors active. All five modules are charged to full voltage. One triggers "spontaneously" – i.e. without the occurrence of a properly timed trigger pulse. In this case the beam kick delivered by the one triggered module is not sufficient to remove the beam from the machine aperture cleanly. It is sufficient to cause the beam to be removed over many turns at limiting apertures around the machine. Most importantly significant beam loss may occur at the Beam Experiments causing damage to the experiment's beam detectors.

It is this mechanism and scenario rather than the quenching of magnets that has been the most significant negative impact of the abort system on RHIC operations.

A subsystem to reduce the impact of prefires is now part of the overall Beam Dump system. The current pulse sent to the magnet for each module is monitored. The signals from the five modules are combined in the ring and produce an additional set of triggers, which are then sent out to all of the modules. If one module prefires, the other four will be triggered within a microsecond. With this configuration active the beam loss at the Beam Experiments has been acceptable. Independent of this new system, other adjustments that fall within the original Beam Dump System description have greatly reduced the occurrence of prefires.

Diagnosing the prefire problem led to an expansion of the planned monitoring equipment for the Beam Dump system. The magnet current pulses from all five modules for both the Yellow and Blue rings are now "logged" – saved into computer memory – with a 10-nanosecond sample rate. A 50-microsecond window of data is collected by oscilloscopes triggered by a pulse occurring on one of the modules in each ring. Voltage waveforms for all of the pulse-forming networks are also logged continuously at the standard 720-Hertz rate.

The circumference of RHIC is 3833.8 m, resulting in a minimum pulse length for the kicker system of 12.8 μs. In order to facilitate the abort system design, a gap of ~1 μsec (corresponding to 4 missing bunches) will be provided. Thus, the kicker pulser and the pulse forming network must be designed with a rise time to achieve the nominal deflection of 1.6 mrad within this gap. After the initial rise, the excitation current will continue to rise by ~45% and oscillate for ~13 μsec, which will provide the necessary horizontal dispersion of the bunches on the face of the absorber.

A beam-based calibration of the strength of the beam dump kick verses PFN voltage was carried out early in the first year of operation. Using Beam Position Monitors in the drift downstream of the kicking magnets it was determined that the required 1.6 mradian kick occurs at the first "dip" in the current pulse (see PFN section below) for 100GeV gold at a PFN voltage of about 27.6 kV.

The timing of the kick relative to the abort gap is also set up by a beam-based procedure each running period after the reference "rev tick" on the beam-sync timing link has been established. The precision required of the kicker pulse timing increases as the abort gap is shortened. The most critical requirement of the timing is to start ramping only after the leading edge of the gap passes the dump kickers to avoid touching beam since the resulting gentle kick will result in beam scraping not in the absorber but rather elsewhere around the ring. The abort gap then has to last long enough to insure that the first beam coming after the gap receives at least the 1.6 mradian kick. The ramping current get to the amplitude of the subsequent first dip (used for the calibration exercise) in approximately 1.1 microsecond.

The ion beams in RHIC will always be bunched, and as mentioned above, a gap of 1 μsec will be left in the circulating beam so that, in principle, the kicker will be able to rise to nominal field without imparting a partial deflection to some of the beam during the risetime. Even a small amount of partially deflected beam has the potential to quench one of the high β quadrupoles. This "empty gap" concept is partially invalidated by Au ions, which leave their rf buckets and "leak" into the gap.

"Gap cleaning" – the removal of any beam that does manage to leak into the abort gap – has been accomplished by exciting a coherent transverse betatron oscillation for the beam within the abort gap driving this beam out of the machine aperture. Sufficient amplitude is achieved by applying repeated kicks generated by a kicker system independent of the Beam Dump system that are resonant with the beam's betatron frequency. The gap cleaning machinery is active throughout the period when the beams are in collision.

As mentioned above, the beam dump kicker must disperse the beam bunches on the face of the dump absorber to preserve the integrity of the dump material. The worst case will be the ejection of the Au beam immediately after acceleration. In contrast to the situation with proton beams, the energy density will be highest at the dump entrance due to the Z^2 dependence of dE/dx. Dynamic stress analysis showed that the dispersal achievable by the kickers was not sufficient to insure that a dump window would not crack due to thermal shock at the design intensity in worst-case conditions. For this reason, it was decided to forego a window design by making the first element of the dump absorber a stress resistant graphite composite known as carbon-carbon (C-C), placed inside the vacuum chamber. This material is designed for Tokamak walls and missile tips, and is essentially impervious to thermal shock.

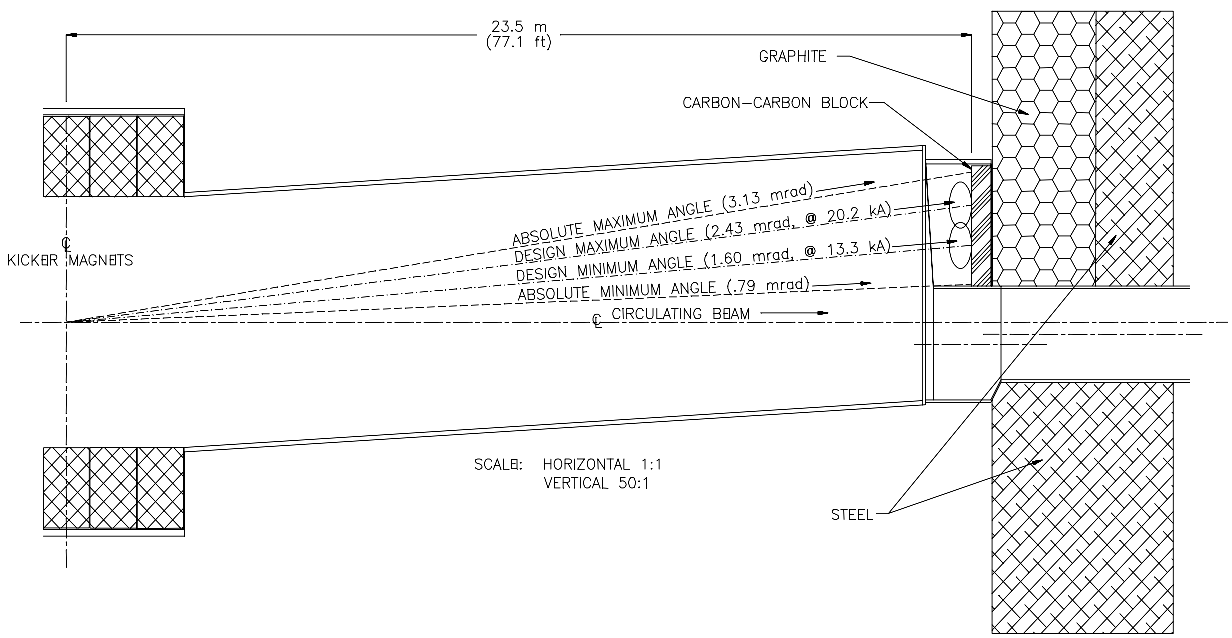

Fig. 6-3. Exaggerated plan view of dump geometry showing beam spots corresponding to acceptance aperture on dump face.

A diagram of the dump proper is shown in Fig. 6-4. As shown, the first element encountered by the extracted beam will be the C-C block, then the vacuum window, ordinary graphite and steel. Since the C-C block out-gasses to some extent, sputter-ion vacuum pumps must be employed to keep the vacuum in the ring sufficiently low. Estimates of the thermal stresses in the various materials of the dump give an adequate margin of safety against cracking and erosion of the C-C material at the design intensity.

Also shown in Fig. 6-4 is the aperture of the dump. At full energy, the circulating beam center line will be displaced horizontally from the physical center of the dump beam tube, so that the ring aperture at the dump is limited to 16.5 mm. This distance corresponds to the 6σ referred to previously. At injection energy, where apertures are tightest, a horizontal orbit bump can displace the beam center line to the physical center of the dump aperture which will then yield over 8.5σ at this location.

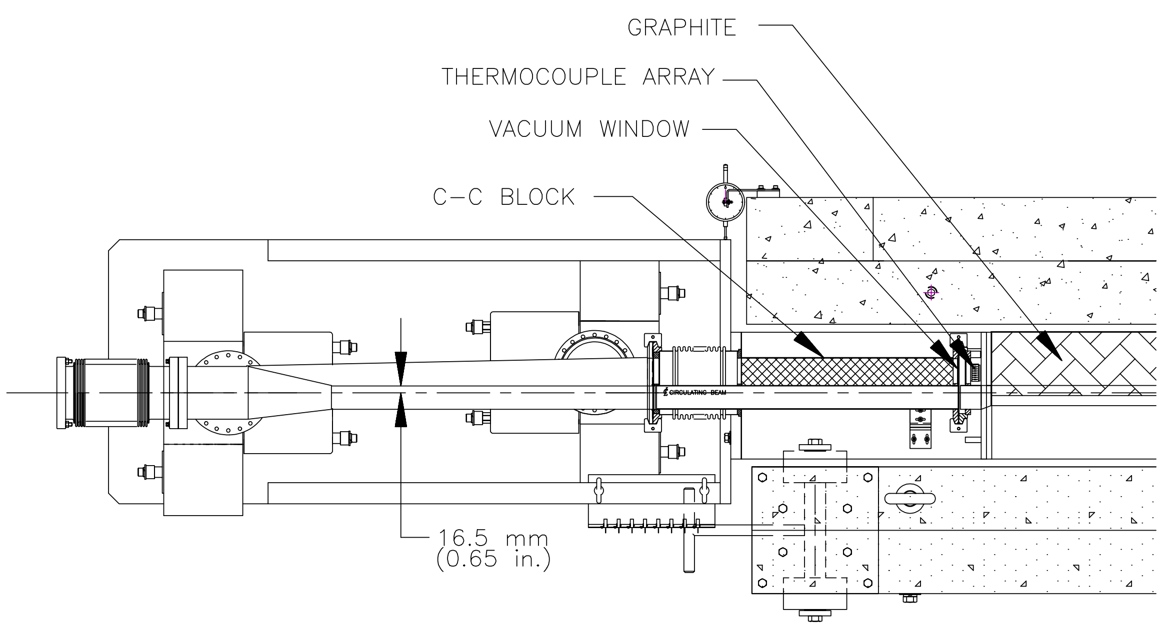

Fig. 6-4. Beam dump absorber details.

Although the dump design described here has a significant margin of safety at the design intensity, it is not clear whether the current design will be adequate for substantially upgraded beam intensities, especially as regards energy deposition in Q4 from secondaries emerging from the dump. Possible upgrades to the internal dump would include vertically deflecting sweeping magnets to increase dispersion of the bunches and a special Q4 magnet with a "liner." Nothing in the current system precludes a future upgrade to a full extraction system to an external dump. Such a system would require a stronger kicker system, the addition of a septum magnet system in place of the current internal dump, and a special Q4 cryostat containing an aperture through which the beam could pass en route to an external dump.